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Greenhouse Gas Emissions from Hydroelectric Reservoirs: What Knowledge Do We Have and What is Lacking?

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1. Introduction

The question that motivated us to write this chapter was “How does hydroelectricity production contribute to the global emissions of greenhouse gases?”. Here, we present an overview of (i) scientific advances on the topic and (ii) aspects of hydroelectric reservoir ecology in the context of greenhouse gas production, consumption and emission.

Electricity production is a challenging issue when it comes to mitigating greenhouse gases (GHG) emissions without risking development goals. Non-renewable energy sources, as fossil fuel burning, account for most of the global energy production (68% in 2007) and are responsible for most of the anthropogenic GHG emissions to the atmosphere (40%, International Panel on Climate Change - IPCC, 2007). Compared to fossil fuels, hydropower has been considered an attractive renewable energy source with the advantage of being less harmful in terms of GHG emissions (International Energy Agency - IEA, 2008). Hydropower currently provides about 16% of the world's electricity supply (IEA, 2008) with many countries depending on it for more than 90% of their supply. Indeed, hydropower is a proven, mature, predictable and typically price-competitive technology. Moreover, it has among the best conversion efficiencies of all known energy sources: 90% efficiency as opposed to up to 50% efficiency of e.g. fossil fuel burning. The historical perception of hydroelectricity as being GHG neutral (Hoffert et al., 1998), however, is now known to be flawed. The concern regarding the GHG emissions by hydroelectric reservoirs has steeply increased since the early 90's, even though it remains unclear what their actual emission is.

Although inland water systems naturally produce and emit carbon to the atmosphere (Cole et al., 2007) different characteristics of hydroelectric reservoirs cause that they often produce and emit more than natural systems, especially in the first twenty years after flooding (Barros et al., 2011). This is mainly due to the usually excessive availability of decomposable organic matter in hydroelectric reservoirs. Not only large amounts of soil and terrestrial vegetation are flooded by damming rivers, but terrestrial organic matter derived from land erosion is continuously flushed into reservoirs as well. The usually high water residence

time in reservoirs as compared to rivers, combined with high inorganic nutrient inputs, favors organic matter decomposition and, thus, the production of two major GHGs – carbon dioxide (CO₂) and methane (CH₄). The amount of CO₂ and CH₄ emitted varies (a) among reservoirs (as function of drainage basin characteristics, reservoir morphology, climate, etc.); (b) within reservoirs (along longitudinal gradients from the tributaries to the dam, before and after the dam, etc.); and (c) over time (with reservoir aging, seasonally, daily, with changes in anthropogenic activities in the drainage basin, and with dam operation depending on energy needs and precipitation regime). Attempts to estimate the amounts of CO₂ and CH₄ emitted to the atmosphere should consider such variability which makes it a complex task.

Despite the complexity of the GHG issue, the effect of damming rivers on the atmospheric GHG concentrations cannot be disregarded. The concern about the impacts of hydroelectric reservoirs on the global GHG budgets has been increasing in the same pace as the construction of new dams. Nowadays, there are at least 45,000 large hydroelectric reservoirs in operation worldwide (World Commission on Dams –WCD, 2000). Moreover, recent inventories estimate the total surface area of world's hydroelectric reservoirs at about 350,000 km² (Barros et al., 2011). The substantial size of some hydroelectric projects and the extensive total surface area globally covered by reservoirs require that research determining the impacts of these systems be done at ever-increasing spatial and temporal scales.

This chapter focuses on the GHG emissions that are due to the landscape transformation (damming a river to form a reservoir) and to reservoir operation to produce electricity. First, the scientific advances towards understanding the role of hydroelectric reservoirs and their environmental effects as sources of GHG are delineated. Then, the metabolic processes involved in GHG production and consumption are described with focus on the two major interacting compartments: the water column and the sediment. Next, the external factors influencing the emission rates from reservoirs are discussed. Finally, an overlook of future perspectives in terms of GHG emissions from hydroelectric reservoirs is presented.

2. Important scientific advances

The ever increasing global energy demand and the concern about the changes in environment have lead to an urge to assess the hydropower 'footprint' in terms of GHG emissions to the atmosphere. Since the early 90's the role of hydroelectric reservoirs as sources or, as the opposite, sinks of GHG has rapidly become a global topic of investigation (**Figure 1**). At least 85 globally distributed hydroelectric reservoirs have so far been studied with focus on GHG fluxes (Barros et al., 2011). The first scientific papers focused on reservoirs located in Canada (e.g. Rudd et al., 1993; Duchemin et al., 1995), Brazil (e.g. Rosa & Schaeffer, 1994; Fearnside, 1995, 1997), Panama (Keller & Stallard, 1994) and French Guiana (e.g. Galy-Lacaux et al., 1997; Galy-Lacaux et al., 1999). Later, reservoirs in Finland (e.g. Huttunen et al., 2002), USA (e.g. Soumis et al., 2004), Sweden (e.g. Aberg et al., 2004; Bergstrom et al., 2004) and Switzerland (e.g. Diem et al., 2007) were studied. Only very recently, GHG emissions from reservoirs located in China, the country with the largest installed capacity in the world, became focus of investigation (e.g. Chen et al., 2009; Wang et al., 2011; Zheng et al., 2011) (**Figure 2**).

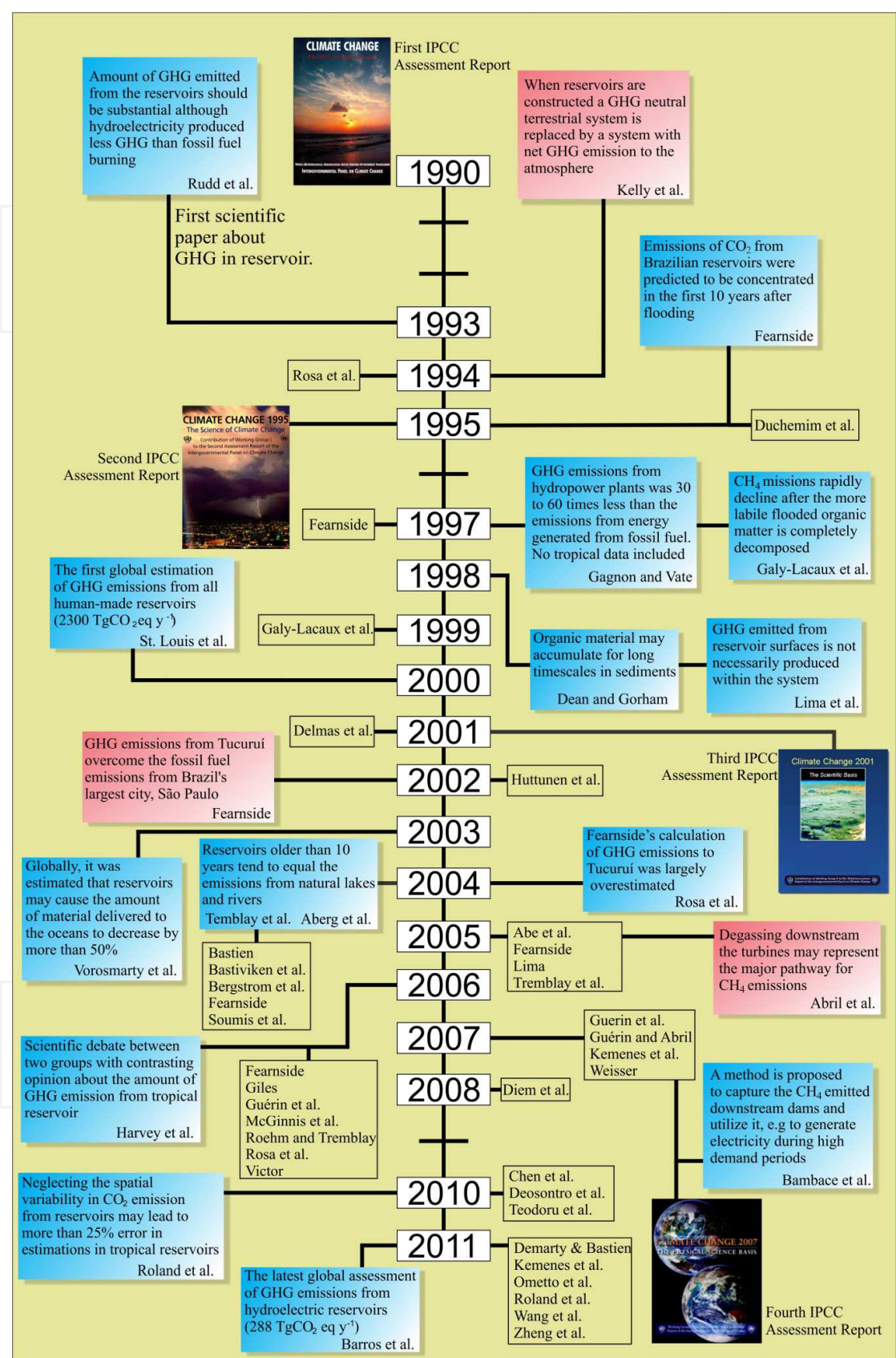


Fig. 1. Timeline of scientific advances regarding the role of hydroelectric reservoirs as sources of GHG to the atmosphere.

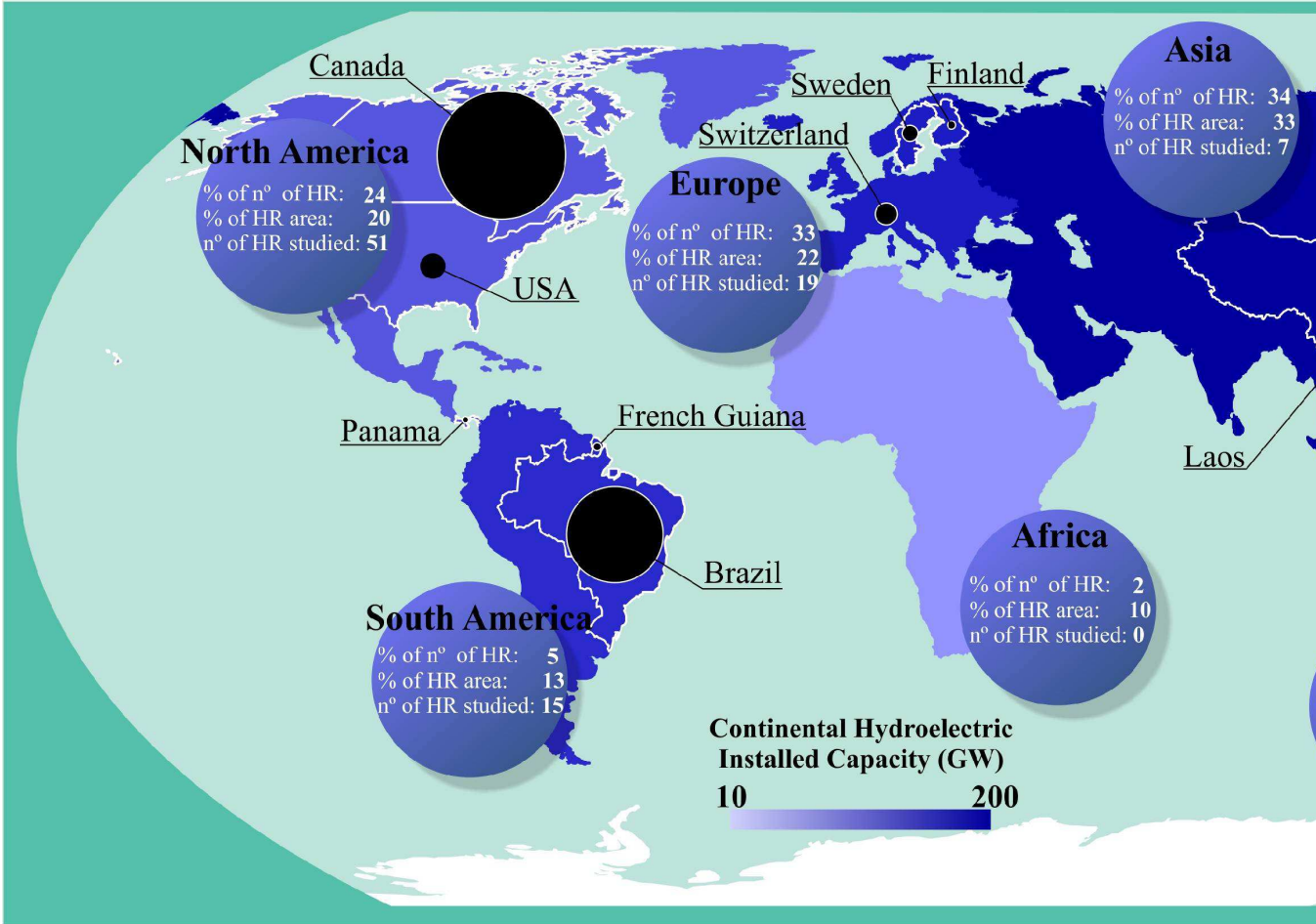


Fig. 2. Global distribution of hydroelectric reservoirs (HR), expressed as the proportion of the total n constructed on each continent, the proportion of the global HR area on each continent and the numb continent. The blue gradient indicates the hydroelectric installed capacity per continent. The black c the number of papers published dealing with GHG emissions from reservoirs located in each countr number and total area of hydroelectric reservoirs were calculated based on ICOLD (2007). The numl approaching GHG emissions from hydroelectric reservoirs were extracted from Barros et al., 2011, C al., 2011, and Zheng et al., 2011.

2.1 GHG emissions – hydropower versus other electricity sources

Historically, the question to which extent hydropower is a GHG-friendly source of energy has been an important one. A first study focusing on reservoirs in northern Canada suggested that the amount of GHG emitted from reservoirs was substantial when compared to emissions from fossil fuel burning (Rudd et al., 1993). A subsequent assessment estimated that GHG emissions from hydropower plants (considering their full lifecycle) was 30 to 60 times less than the emissions from energy generated from fossil fuel (Gagnon & Van de Vate, 1997). This assessment, however, did not include data from hydroelectric reservoirs in tropical climates which were later found to have relatively high emissions. Yearly GHG emissions from a large reservoir located in the Brazilian Amazon (Tucuruí reservoir), for example, was argued to overcome the fossil fuel emissions from Brazil's largest city, São Paulo (Fearnside, 2002). Others criticized this finding and considered the reservoir GHG emissions to be largely overestimated (Rosa et al., 2004). This critic triggered a scientific debate between two groups with contrasting opinions (Fearnside, 2004; Rosa et al., 2004; Cullenward & Victor, 2006; Fearnside, 2006; Giles, 2006). Although the groups disagree on the amount of GHG emitted from hydropower in relation to other energy sources, they do agree that GHG emissions from tropical reservoirs are large. Emissions from the Brazilian Curuá-Una reservoir, for instance, were argued to overcome the emissions from oil generated electricity (Fearnside, 2005). Later, Brazilian hydroelectric reservoirs were shown to emit less carbon per energy production than thermonuclear power plants, with the exception of some cases of low power density, i.e. low energy production/flooded area ratio (Dos Santos et al., 2006). Finally, a recent inventory including several Brazilian reservoirs located both in the Amazon and in other biomes showed that the GHG emissions per energy produced (GHG/MWh) are lower in most reservoirs, regardless of their age (Ometto et al., submitted). This inventory showed that the highest GHG/MWh rates occur in large Amazonian reservoirs with low energy production rates.

Overall, hydropower may thus produce electricity with one of the lowest life-cycle GHG emissions (Weisser, 2007), especially in non-tropical regions (Barros et al., 2011). Nevertheless, the important role of hydroelectric reservoirs in the global GHG dynamics is unquestionable.

2.2 Organic matter and GHG

The high GHG emissions from hydroelectric reservoirs were originally argued to be due to the decomposition of flooded organic soil and vegetation (Rudd et al., 1993; Abril et al., 2005). This understanding of the role of reservoirs needs to take into account the balance between GHG emissions and consumption prior to and after the impoundment of a certain area (Teodoru et al., 2010). Net GHG emission was considered close to zero prior to impoundment, as emissions from rivers would be compensated by the sink of terrestrial photosynthesis. After flooding, the GHG neutral terrestrial system is replaced by a system with net GHG emissions to the atmosphere (Kelly et al., 1994).

This focus on the flooded organic matter further lead to the understanding that with reservoir aging, the amount of decomposable flooded organic matter would be gradually reduced and, thus, GHG emissions from reservoir surfaces would decline. Indeed, a long-term assessment of GHG emissions from the tropical Petit Saut reservoir showed that CO₂ and CH₄ emissions are high in the first two years after impoundment after which emissions

rapidly decline when the more labile flooded organic matter is decomposed (Galy-Lacaux et al., 1997; Galy-Lacaux et al., 1999). Emissions of CO₂ from Brazilian reservoirs were predicted to be concentrated in the first 10 years after flooding (Fearnside, 1995, 1997). Later, evidence from Canadian systems showed a similar trend and suggested that CO₂ emissions from reservoirs older than 10 years tend to equal the emissions from natural lakes and rivers (Tremblay et al., 2004). Similar results were also reported for a Swedish reservoir which was compared with a natural lake (Aberg et al., 2004). Moreover, a significant negative relationship between age and GHG emissions was registered for temperate reservoirs (St Louis et al., 2000) and for reservoirs located all over the globe (Barros et al., 2011).

Nevertheless, other sources of carbon to reservoirs besides flooded organic matter should be taken into consideration. During their complete lifetime, organic matter and nutrients from the drainage basin are continuously flushed into the systems through tributary rivers (Fearnside, 1995; Roland et al., 2010) and aquatic primary production rates tend to increase (Bayne et al., 1983). Once in the reservoirs, organic matter derived from the drainage basin and from aquatic primary production mineralizes at different rates, the latest being usually more labile (Kritzberg et al., 2005; Vidal et al., 2011). Most of the organic matter mineralization and, thus, most of the GHG production in reservoirs occurs in the sediment (Aberg et al., 2004; Abe et al., 2005). Furthermore, it has become clear that GHG emitted from reservoir surfaces is not necessarily produced within the system, as tributary rivers may export large amounts of GHG to reservoirs (e.g. Lima et al., 1998).

2.3 Global emission estimates

From 2004 on, the studies were marked by a more holistic approach incorporating emissions from water passing through the turbines and downstream of dams, as has been done earlier in the tropical Petit Saut reservoir (Galy-Lacaux et al., 1997). Continuous measurements from Petit Saut reservoir lead to a 10-year assessment of GHG emissions which showed that degassing downstream the turbines may represent the major pathway for CH₄ emissions (Abril et al., 2005). High emissions downstream of dams were registered in other tropical (e.g. Guerin et al., 2006; Kemenes et al., 2007, 2011) and in temperate reservoirs as well (e.g. Soumis et al., 2004; Abril et al., 2005; Roehm & Tremblay, 2006). Motivated by the idea of mitigating CH₄ emissions from reservoirs, a method was proposed to capture the CH₄ emitted downstream dams and utilize it, for instance, to generate electricity during high demand periods (Bambace et al., 2007).

More recently, attention has turned to the spatial variability on GHG emissions within reservoirs. Measurements in tropical reservoirs suggested that neglecting the spatial variability in CO₂ emission from reservoirs may lead to more than 25% error in estimations (Roland et al., 2010). In the same year, spatial variability in CO₂ fluxes from temperate reservoirs was shown to decline with time after impounding (Teodoru et al., 2010). The importance of considering the spatial variability in CH₄ emissions was also addressed based on data from Chinese reservoirs (Zheng et al., 2011).

The first global estimation of GHG emissions from reservoirs was published in 2000 (St Louis et al., 2000). This assessment considered emissions from reservoirs of all uses, including irrigation, water supply, energy generation and others. Based on 21 systems located in temperate climate (i.e. Canada, United States, and Finland), the authors calculated

average emissions of $1400 \text{ mg m}^{-2} \text{ d}^{-1}$ of CO_2 and $20 \text{ mg m}^{-2} \text{ d}^{-1}$ of CH_4 . Their estimated emissions from tropical reservoirs ($3500 \text{ mg m}^{-2} \text{ d}^{-1}$ of CO_2 and $300 \text{ mg m}^{-2} \text{ d}^{-1}$ of CH_4), though, were based on data from a very small number of systems (four) and might have been overestimated due to the inclusion of young reservoirs (1-2 year old) which have high emissions. After estimating the global area occupied by all reservoirs types, the authors calculated the global emissions of GHG to be 273 Tg of CO_2 and 48 Tg of CH_4 per year. Considering that CH_4 global warming potential is 25 times higher than that of CO_2 (IPCC, 2007), these emissions corresponded to 2,600 Tg of CO_2 -equivalents per year.

After 2000, there was an important increase in the amount of data on GHG emissions from reservoirs located in both temperate (e.g. Huttunen et al., 2002; Aberg et al., 2004; Bergstrom et al., 2004; Soumis et al., 2004; Tremblay et al., 2004; Duchemin et al., 2006) and tropical regions (e.g. Delmas et al., 2001; Fearnside, 2002; Rosa et al., 2004; Abril et al., 2005; Guerin et al., 2006; Guerin et al., 2007). Comparisons between emissions in different regions were applied as tools to understand the factors controlling emissions from reservoirs. For example, CO_2 emissions from Swedish reservoirs were lower than those reported for other boreal regions, which was attributed to the fact that in Sweden often comparatively small areas with thin layers of organic soil are flooded for reservoir construction (Bergstrom et al., 2004). In 2011 a review of the achievements in 20 years of measurements of CH_4 emission from tropical and equatorial reservoirs came out (Demarty & Bastien, 2011). The document claims that GHG emissions might have been underestimated in the tropics due to the neglect of CH_4 emissions.

Finally, the latest global assessment of GHG emissions from hydroelectric reservoirs compiled data from 85 globally distributed systems which account for about 20% of the global area occupied by hydroelectric reservoirs (Barros et al., 2011). The authors estimated that hydroelectric reservoirs globally emit about 51 Tg of carbon per year (48 Tg per year as CO_2 and 3 Tg per year as CH_4 or 288 Tg of CO_2 -equivalents per year) which is low compared to the first global estimation (321 Tg of carbon per year, St Louis et al., 2000). This difference is argued to be caused (i) by the greater amount of data currently available and (ii) by the smaller area occupied by hydroelectric reservoirs (350.000 km^2 , Barros et al., 2011) when compared to the area occupied by all types of reservoirs ($1.500.000 \text{ km}^2$, St Louis et al., 2000). Furthermore, this latest assessment showed that GHG emissions are correlated to reservoirs age and latitude, with the highest emission rates occurring in the Amazon region.

3. Environmental effects of hydroelectric reservoirs and the consequences for GHG emissions

By definition, hydropower is a renewable source of electricity in which power is derived from the energy of water moving from higher to lower elevations. The amount of energy generated depends both on the accumulated water volume and on the difference in height between the water inlet and the outflow. While dams perform an important function, their effect on landscapes is remarkable: a fragment of river and its adjacent terrestrial environment are transformed in a new freshwater system, the reservoir. According to recent global inventories, $10,800 \text{ km}^3$ of water were impounded in reservoirs (all kinds of reservoirs, e.g. irrigation, water supply, flood control, and aquaculture) in the last half century, causing the sea level to reduce by approximately 30 millimeters (Chao et al., 2008). The construction of reservoirs clearly represents, thus, one of the major human impacts on the hydrological cycle. The effects of such transformation, however, surpass the hydrological level. Impounded areas undergo a cascade of changes which influence, directly or indirectly, the local GHG fluxes (Figure 3).

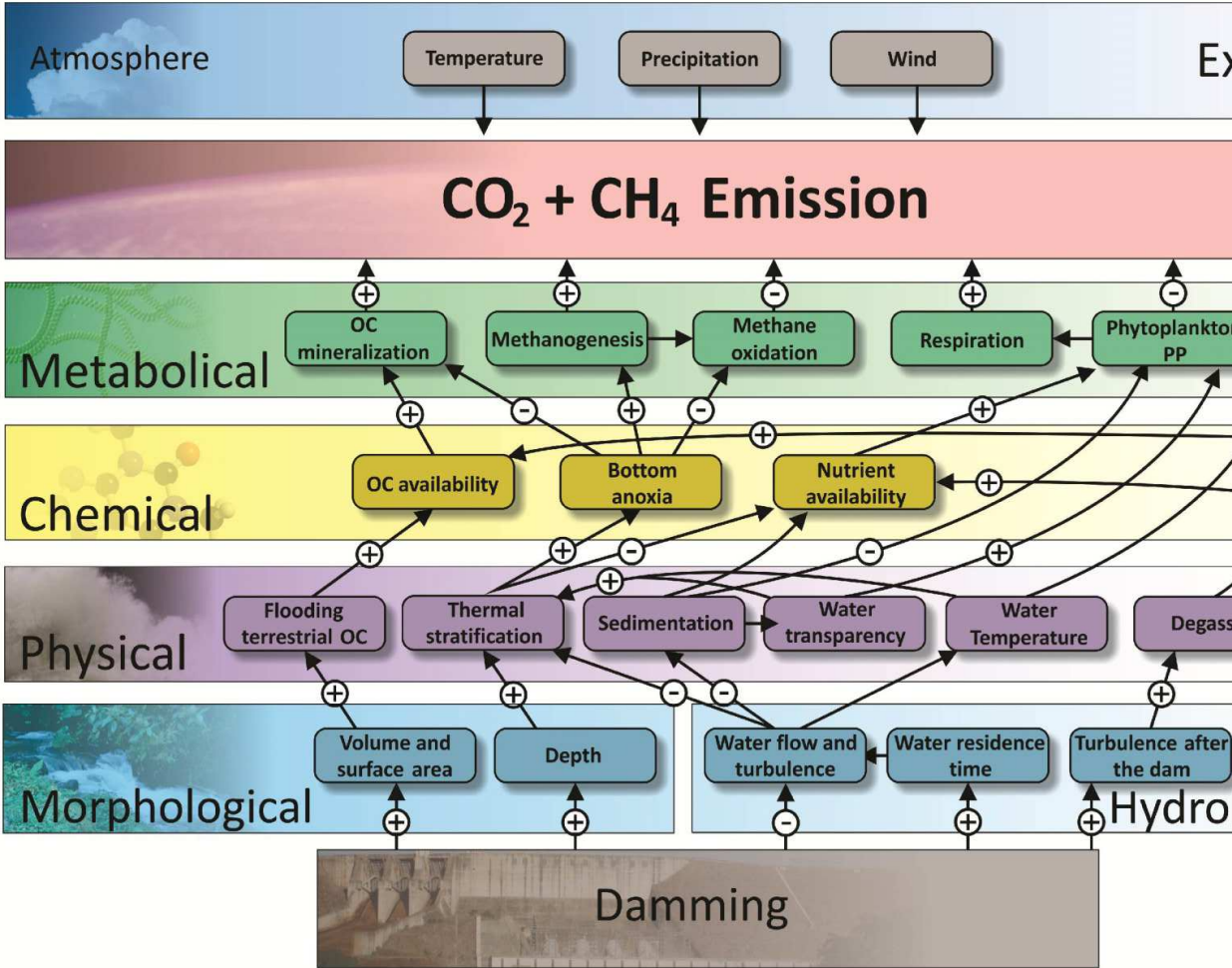


Fig. 3. Diagram illustrating some of the major impacts of damming rivers and their effects on GHG emissions. The hydrological impacts of damming rivers trigger a cascade of shifts in the physical and chemical conditions, leading to indirect (through changes in metabolism) and direct changes in GHG fluxes. External factors like atmospheric conditions and drainage basin characteristics also influence GHG emissions. GHG emissions are mainly related to atmospheric conditions and drainage basin characteristics. OC = organic carbon; PP = primary production. Arrows with the (+) symbol represent positive effect; arrows with the (-) symbol represent negative effect.

Prior to dam construction, rivers generally have rapid water flow rates which vary with drainage basin size and topography and respond to the seasonality in the upstream precipitation regime. Precipitation regimes also control variations in river water level, which usually varies within a predictable range. Rivers naturally emit large amounts of CO₂ due to terrestrial organic matter decomposition (Cole et al., 2007; Tranvik et al., 2009). Because the turbulent flow keeps oxygen concentrations high, CH₄ emissions hardly occur (Abril et al., 2005) except in highly organic matter-rich rivers (e.g. Lima et al., 1998). In compensation, terrestrial vegetation surrounding a river course usually functions as a CO₂ sink, since photosynthesis tends to exceed respiration. Furthermore, rivers play a crucial role in removing carbon from the global cycle by carrying large amounts of terrestrial material to the ocean (Schlesinger & Melack, 1981) where it is partially permanently buried (Hedges & Keil, 1995; Hedges et al., 1997).

The construction of dams implies the extension of flooded area. This implies that flooded terrestrial vegetation no longer performs photosynthesis. Instead, the organic matter stored in vegetation, as well as in flooded soil, becomes available for bacterial decomposition (with subsequent release of CO₂ and CH₄). It means that the flooded terrestrial area shifts from being a net sink to a net source of carbon to the atmosphere. The amount of GHG emitted from decomposition of flooded vegetation depends on the size of the flooded area, as well as on the quantity and quality of organic matter.

Moreover, the enlargement of flooded area with reservoirs formation comes with an increase in water volume and causes water residence time (or turnover time) at individual impoundments to increase from less than one day to several years in the case of large dams. The reduction of river water velocity in the headwater of reservoirs results in a decreased sediment-carrying capacity and in the retention of particulate matter transported by rivers. Reservoirs are usually constructed at the lower end of large drainage basins, where rivers usually carry terrestrial material derived from the entire upstream drainage basin. Despite being energetically favourable – it guarantees maximal water inflow and, thus, enhances the potential for energy generation – this strategy implies that high amounts of terrestrial material constantly flow into and accumulate in the reservoirs. Globally, it has been estimated that reservoirs may cause the amount of material delivered to the oceans to decrease by more than 50% (Vorosmarty et al., 2003). Organic matter settled at the bottom of the reservoir has a higher chance to be mineralized than when it would have settled at the ocean bottom (see section 4 for details). As a consequence the net global emission of GHG is enlarged. Nevertheless, it should also be remarked that part of the organic material deposited in the sediment of reservoirs is not mineralized and may accumulate for long timescales (Dean & Gorham, 1998).

Due to the transition from a turbulent-shallow river to a relatively static-deep system, reservoirs tend to undergo thermal stratification, especially in warm regions. The process of thermal stratification is triggered by differences in water density and leads to the formation of water layers: epilimnion (top), metalimnion (intermediate) and hypolimnion (bottom). Once these layers are formed, there is no mixture between top and bottom layers unless some stress (e.g. wind, shift in temperature or increase in water inflow from rivers) breaks water column stability. The establishment of stratification has important effects on oxygen dynamics and, thus, on GHG emissions from reservoirs (see section 4 for details).

4. GHG dynamics in reservoirs – an ecological assessment

The potential of any aquatic system as source or sink of GHG to the atmosphere is ultimately determined by (i) the concentration of GHG dissolved in the water as related to the atmospheric GHG concentration and (ii) the solubility of the gases in the water. The processes of production, consumption and emission of GHG in hydroelectric reservoirs are dependent on their hydrological characteristics, which make of them especial sites in terms of GHG dynamics when compared to other aquatic systems.

4.1 Water column and sediment

Most of the routes of production and consumption of CO_2 and CH_4 are controlled by the aquatic biota metabolism (**Figure 4**). In a nutshell: aerobic respiration produces CO_2 which is consumed through photosynthesis; methanogenic bacteria produce CH_4 which is consumed by methanotrophic bacteria. An exception to the general pattern of biota mediating CO_2 production is the process of photo-oxidation, i.e. the break-down of dissolved organic molecules by solar radiation with the production of several compounds among which CO_2 is the more abundant (Soumis et al., 2007; Bastien, 2005). Production and consumption of GHG within reservoirs, however, are not the only processes controlling GHG stocks in the water column. Tributary rivers flowing into reservoirs may carry variable amounts of GHG

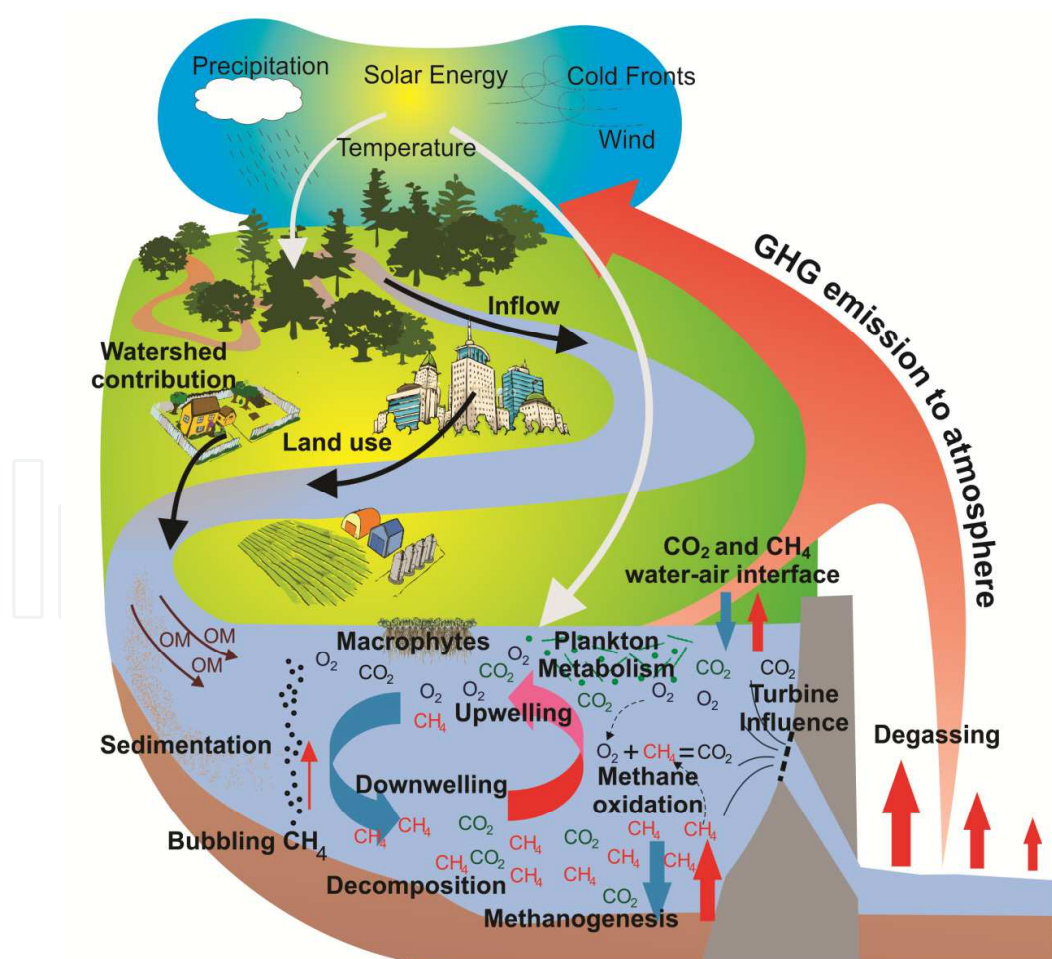


Fig. 4. Main pathways of GHG production, consumption and emission to the atmosphere.

(mostly CO_2 but also CH_4). Moreover, dissolved CO_2 can flow into reservoirs from both surface and groundwater runoff.

A global assessment of lakes with a worldwide distribution showed that most of the lakes in the world are net sources of CO_2 to the atmosphere (Cole et al., 1994; Sobek et al., 2005). The frequently high CO_2 concentrations are argued to rely on the high influx of organic matter and the consequent excess respiration by heterotrophic bacteria. The high availability of terrestrial organic matter in hydroelectric reservoirs causes particularly high heterotrophic respiration in these systems. Especially in young reservoirs where the availability of decomposable organic matter is high, the respiration by aerobic planktonic bacteria is elevated (Roland et al., 2011).

Mineralization may also occur anaerobically in the water column of stratified reservoirs (Abril et al., 2005). With the establishment of stratification, the oxygen consumption due to organic matter mineralization in the bottom layers of reservoirs is no longer offset by water exchange with top oxygenated water layers (see section 3 for details). Thus, bottom water layers become gradually anoxic. Under anoxic conditions, methanogenic bacteria metabolize organic compounds, hydrogen and CO_2 into CH_4 (methanogenesis), leading to high CH_4 concentrations in the bottom layer of reservoirs (Abril et al., 2005). Due to the persistent stratification of reservoirs located in warmer regions, methanogenesis is usually an important pathway of GHG production in those systems (Demarty & Bastien, 2011). However, most of the CH_4 produced in the water column of reservoirs tend to be emitted to the atmosphere as CO_2 due to the oxidation by metanotrophic bacteria at the top oxygenated water layer (Guerin & Abril, 2007).

The overall GHG production in the water column of reservoirs is small compared to the production in the sediments. Great amounts of particulate organic matter transported through rivers tend to sedimentate in reservoirs. Sedimentation is also the fate of organic matter produced by algal photosynthesis in the water column. Once in the sediment, organic matter (i) is mineralized by aerobic or anaerobic bacteria and released as CO_2 and CH_4 (among other compounds) to the water column, (ii) is re-suspended, or (iii) remains buried. The relative importance of each of these processes is system-specific and influences the overall role of a reservoir as net sink or source of GHG to the atmosphere.

Mineralization leads to a general chemical-metabolic gradient within undisturbed sediment profiles. Aerobic mineralization is restricted to the top sediment layer, which may have variable thicknesses depending (i) on the hypolimnetic oxygen concentration, (ii) on the oxygen diffusion coefficient, which is a function of sediment density, sediment porosity, temperature and turbulence at the sediment-water interface and (iii) on the rate of oxygen consumption during organic matter mineralization. Below this top oxygenated sediment layer, anaerobic processes dominate sediment metabolism. While CO_2 is the only GHG gas produced as a result of aerobic decomposition, anaerobic processes produce CH_4 in addition to CO_2 . These gases accumulate in sediment pore-water and tend to be released in the water column as a consequence of the difference between concentrations in these two compartments.

Diffusive CH_4 tends to be oxidized into CO_2 by metanotrophic bacteria at the oxygenated top sediment layer or in the water column. The extent of CH_4 oxidation in the water column depends on oxygen availability and, thus, may be higher in deeper reservoirs (Lima, 2005).

It has been shown, e.g., that oxidation in the water column of Petit Saut reservoir can reduce CH₄ emissions at more than 85% (Guerin & Abril, 2007). However, in very organic-rich sediments, the high rates of mineralization combined with the hydrophobic characteristic of CH₄ molecule, can cause CH₄ to form bubbles which tend to be quickly emitted to the atmosphere (Bastviken et al., 2004; McGinnis et al., 2006). Even though the formation of CH₄ bubbles is favoured by high temperatures, temperate reservoirs may also emit significant amounts of CH₄ through bubbling (e.g. Delsontro et al., 2010).

Both aerobic and anaerobic mineralization of organic matter release large amounts of inorganic nutrients, in addition to CO₂ and CH₄, in the water column of reservoirs. The availability of inorganic nutrients, especially phosphorus, combined to the usually high light penetration depth in reservoirs (due to sedimentation of suspended material) favours CO₂ uptake by photosynthesis. Photosynthesis in reservoirs, as in any other aquatic system, is performed by phytoplankton in the water column, attached algae (periphyton) and aquatic plants (macrophytes). However, due to the usually high depth (and high 'total volume/littoral volume' ratio) of reservoirs, the relative importance of periphyton and macrophyte tends to be low compared to the importance of phytoplankton. In eutrophic reservoirs (i.e. high nutrient concentrations and high phytoplankton production) photosynthesis can cause a strong reduction in CO₂ concentrations turning the reservoirs into a sink of atmospheric CO₂. This occurs in reservoirs worldwide, regardless of age or latitude (Barros et al., 2011). The number of reservoirs acting as carbon sinks is, however, low as compared to CO₂ emitting reservoirs.

4.2 GHG flux through the water-atmosphere interface

The excess GHG in the water column of reservoirs tend to be emitted to the atmosphere. Emissions can occur through (i) molecular diffusion at the water-air interface (e.g. Roland et al., 2010; Teodoru et al., 2010), (ii) bubbling from the sediment (e.g. Abe et al., 2005; Lima, 2005) (iii) degassing from water passing at the turbines (e.g. Kemenes et al., 2007, 2011) or (iv) turbulent degassing in downstream rivers (e.g. Guerin et al., 2006) (**Figure 4**).

Diffusive fluxes of CO₂ and CH₄ at the water-atmosphere interface are dependent on the existence of a concentration gradient between these two compartments. If the water at the surface of a reservoir is supersaturated with CO₂ or CH₄ in relation to the atmosphere, gas fluxes occur towards the atmosphere. If, on the other side, surface water is under-saturated in relation to the atmosphere, gas fluxes are from the atmosphere to the water. In the latter case, the reservoir surface represents a sink of atmospheric carbon. The amount of GHG flowing through water-atmosphere interfaces depends on gas solubility in water. Gas solubility is negatively related to temperature and positively related to pressure, according to Le Chatelier's principle. Thus, GHG emissions through diffusion tend to be higher in reservoirs located in warmer regions and at lower altitudes. The surfaces of reservoirs are usually dominated by diffusive fluxes of CO₂, even in cases in which bottom anoxia leads to high CH₄ production (Barros et al., 2011). This is due to the intense oxidation of diffusive CH₄ by methanotrophic bacteria above the interface between anoxic and oxygenated water layers.

On the other hand, GHG emissions through bubbling are dominated by CH₄. This is due to the very low CH₄ solubility in water, which permits the formation of bubbles varying in size

from 2 to 8 millimetres (Delsontro et al., 2010). The bubbles are usually formed in the sediment of reservoirs, under anoxic conditions. Most of the CH₄ emissions in shallow reservoirs occur through bubbling whereas CH₄ bubbles are usually dissolved in the water before reaching the surface in deep reservoirs.

The process of energy generation by the turbines of hydroelectric reservoirs leads to two pathways of GHG emission that do not occur in artificial reservoirs built for other purposes (e.g. irrigation, water supply, flood control, and aquaculture): turbulent degassing of water passing through turbines (energy generation unities) and degassing downstream of dams. The water inlet to generate energy is frequently located in medium or lower parts of the dam which means that water from deep layers of the reservoirs passes through the turbines. These deep water layers are usually CO₂ and CH₄-rich due to both high mineralization rates and high water pressure (i.e. high gas solubility). By passing through the turbines, the gases are exposed to a low pressure and high temperature condition which favors rapid emissions to the atmosphere (Kemenes et al., 2007). Despite the usually high GHG emissions at the turbines, high amounts of both CO₂ and CH₄ remain dissolved in the water downstream the dams. GHG produced in reservoirs may be encountered at sites as far as 40 km downstream of the dam (Guerin et al., 2006).

5. External factors affecting the processes driving GHG emissions to the atmosphere

The great variation in GHG emissions from hydroelectric reservoirs in different parts of the globe is explained by the effect of climate and drainage basin characteristics on GHG dynamics. Climate affects the inputs of carbon from land to the aquatic environment and the rates of GHG production and consumption. Moreover, wind, precipitation and temperature may have important effects on the rates of gas exchange in the water-atmosphere interface. This section brings an overview of some important processes and external factors influencing GHG emissions from freshwater systems with focus on the dynamics of hydroelectric reservoirs.

5.1 Wind

Wind is the major source of energy for water movement in lakes and reservoir. The wind stress at the water surface can results in small turbulence, horizontal currents, vertical currents, surface waves and internal waves (seiches). Where and how those processes will emerge and behave depends on a series of factors such as the size and the shape of water surface, fetch, wind direction, temperature, and surrounding terrain. The response of reservoirs to wind stress depends mainly on the morphometric characteristics of the basin and its location. Reservoirs are typically built in valleys, after confluence of several tributaries. It usually results in long and dendritic water bodies (Ford, 1990), contrasting to the generally circular- or bowl-shaped natural lakes. Therefore, depending on the surrounding terrain, wind can blow aligned with the main-long fetch, increasing its effect over water surfaces. This effect, however, is limited by the dendritic geometry or reservoir, resulting in more complex circulation patterns in certain parts of reservoirs.

Wind effect strongly impacts on GHG emissions. Turbulence, for example, influences the velocity of gas transfer at the water-atmosphere interface (Wanninkhof, 1992). The role of

wind on GHG emissions, however, is not restricted to causing surface turbulence. Wind can also cause deep water circulation and transport of dissolved compounds.

The overall picture that emerges is that reservoirs are highly temperature stratified in summer and only weakly forced by wind, while in spring/winter the mixing process is enhanced by high wind velocity. During high velocity wind events surface water moves toward the shore, where the water piles up and sinks in the process known as downwelling. At the same time at the opposite side, surface water is replaced by water that wells up from below (upwelling) (Monismith, 1985; Stevens & Imberger, 1996; Macintyre et al., 2002; Farrow & Stevens, 2003). However, wind direction and persistency are of great importance as well. Persistent wind aligned with the main reservoir body – resulting in a large fetch – is able to promote downwelling/upwelling (d/u) even at low velocities (Assireu et al., 2011). At the downwelling side of a reservoir, CH₄ oxidation plays an important role, changing CH₄ into CO₂ during the downward dissolved oxygen transport and reducing the CH₄ emission to the atmosphere. At the upwelling side of reservoir, the GHG flux to the atmosphere is enhanced due to the high CO₂ and CH₄ concentrations of emerging water. This clearly influences the spatial variability of GHG emissions within reservoirs (Roland et al., 2010). It was suggested that frequent d/u events in the tropical Manso reservoir could enhance CO₂ emissions with approximately 12% (Assireu et al., 2005; Ometto et al., 2011).

5.2 Precipitation

Precipitation can vary markedly in intensity and frequency from one year to another. Such variability can generate different kinds of seasonal patterns, modifying water turnover time and changing the intensity of environmental processes occurring in the water column of aquatic systems (Armengol et al. 1999). Furthermore, the external loading of organic matter and other compounds to the system often increases with intensive precipitation events. The intensity of these loadings depends on land use, vegetation cover and landscape patchiness (Rybak, 2001). Rain-induced high primary productivity has been observed in some African lakes (Lemoalle, 1975; Melack, 1979; Thomas et al., 2000). In tropical regions, the first rains after the start of the rainy season are expected to a lot of carbon into the reservoir that can be assimilated by bacterioplankton or be buried in the sediment. However, if the residence time of the water is very short, with high flushing rate, most of this carbon and nutrients will not remain long in the system (Amarasinghe & Vijverberg, 2002).

Precipitation also affects CO₂ transfer at the air-water interface. Impinging raindrops causes turbulence, enhancing CO₂ flux across the air-water interface (Takagaki & Komori, 2007). This means that, depending on the difference of gas concentrations between water and atmosphere, the emission/absorption of GHG in aquatic systems can be enhanced by increasing precipitation rates. The rainfall effects can be significant to the local CO₂ budget between water and atmosphere during the rainy season but are not as important to the whole system budget as the wind share effect.

5.3 Temperature

Changes in temperature may affect, directly and indirectly, all processes involved in the production, consumption and emission of GHG in reservoirs. For example, respiration

(Sand-Jensen et al., 2007), primary production in the water column (Flanagan et al., 2003) are strongly influenced by temperature. Although both processes tend to increase with warming, it has been argued that respiration has usually a stronger response (Rivkin & Legendre, 2001; Biddanda & Cotner, 2002; Lopez-Urrutia et al., 2006; Sand-Jensen et al., 2007), leading to a net increase in CO₂ production under warmer conditions (Kosten et al. 2010). Moreover, evidences from lakes located in different climate regions have shown that more mineralization occurs (with further CO₂ and CH₄ production) and less carbon is buried in the sediment of warmer systems (Gudas et al., 2010).

Indeed, GHG emissions are higher in reservoirs located in warmer latitudes (Barros et al., 2011). The positive relationship between GHG emissions and temperature implies that environmental changes causing temperature to vary affects the role of hydroelectric reservoirs as GHG sources. Based on the predicted scenarios of global change in temperature (IPCC, 2007) GHG emissions from reservoir will increase, especially in cold regions.

5.4 Drainage basin and river input

Large impoundments may show different zones in terms of CO₂ emission because those fluxes are dependent on flooded biomass and watershed input of organic matter. Compared to natural lakes, reservoirs tend to have shorter water residence times and more complex heterogeneity due to the presence of one or more major water inlets, instead of multiple diffuse water sources characteristic for most natural lakes (Kennedy et al., 1985; Kennedy & Walker, 1990). Reservoirs are intrinsically linked to the rivers that feed them (Baxter, 1977), creating a river-reservoir continuum, in which water and sediment inputs are functions of the land use in the watershed (Kelly, 2001). Watershed land use is often highly correlated with algal cell and nutrients concentrations as has been shown for seven subtropical reservoirs (Burford et al., 2007). This clearly indicates that in order to understand and predict GHG emissions from reservoirs, features of the drainage basin have to be taken into account.

Another important factor to be considered is the difference between the densities of river and reservoir water. When a river reaches a reservoir the water plunges and can flow along the surface (overflow), intermediate (interflow) or deep (underflow) layer, depending on the difference between the water temperature and physical characteristics (e.g. total dissolved solids and suspended solids) (Martin & McCutcheon, 1999). The fate of organic matter influx largely depends on the way the incoming water flows into the reservoirs. If incorporated into deeper layers, anoxic conditions facilitate degradation of organic matter into CH₄. The picture becomes more complicated when, due to the complexity of the system and hydrodynamic factors of the river entrance, waves arise in the interface between river/reservoir water. These waves cause transport of water from the nutrient-rich and GHG-rich deep layer to the surface layer (Assireu et al., 2011).

6. Future perspectives

It is now clear that hydroelectric reservoirs represent a renewable but not a carbon-free source of electricity. Attempts to determine the carbon footprint of hydropower production have led to significant scientific advances (see section 2 for details). However, it is still a

long way towards a full assessment of the role of hydroelectric reservoirs as sources of GHG to the atmosphere. The major gaps to be filled by future research are related to the quality of current carbon budget estimations. However, other issues need attention, e.g. the outcomes of removal of dams and the development of mitigation strategies.

The assessment of the net role of reservoirs as sinks or sources of GHG to the atmosphere requires more than measurements of carbon fluxes at the water-atmosphere interface of reservoirs. For example, the net change in the carbon cycle due to reservoir construction should consider pre-impoundment carbon sinks and sources from the original river course and the adjacent terrestrial landscape (Teodoru et al., 2010). Scenarios of pre- and post-impoundment fluxes, however, are neglected by most estimates of emissions. Even more importantly, there is a need to evaluate the net effect of reservoir as sink of atmospheric carbon (St Louis et al., 2000; Barros et al., 2011), by comparing carbon burial in reservoirs with carbon burial prior to impoundment (i.e. in the ocean).

The role of reservoirs sediment in the global carbon cycle is still poorly understood. Despite the importance of sediment as the main site for organic matter mineralization and GHG production (especially CH₄) sediment carbon fluxes in reservoirs are restricted to few measurements (e.g. Aberg et al., 2004; Abe et al., 2005). Additionally, reservoirs accumulate large amounts of carbon in the sediment, which compensates at least part of the emissions. It has been estimated that approximately 400 gC m⁻² y⁻¹ is buried in reservoirs (Dean & Gorham, 1998; Mulholland et al., 2001). This estimation, however, is based on non-standardized methods which consider, e.g. loss in water storage capacity of reservoirs in the USA and constant values for carbon content and sediment density. There is an urgent need, thus, for research focusing on this potential carbon sink pathway.

Another important source of errors in carbon budgets relies on neglecting variability. Both the neglected variability among and within reservoirs as well as variability over time impacts the precision of carbon flux estimates. The persistent increase in the amount of data, by itself, may contribute to equal out the errors of local and global estimations. Nevertheless, addressing all possible sources of variability is an important task for future research on GHG emissions from reservoirs.

Regarding the variability among reservoirs, the limited amount of data from reservoirs located in the tropics was, until recently, severely limiting the precision of GHG emission estimations from reservoirs (e.g. St Louis et al., 2000). Within the last decade, many tropical reservoirs have become focus of study, permitting a better evaluation of the latitudinal effect on emissions (Barros et al., 2011). Nevertheless, there is still a great need for research in the tropics, since this is where most of the potential for new dams remains (Figure 2). Future research on tropical reservoirs should seek for better estimations of CH₄ emissions, which seems to have been seriously underestimated in the last two decades (Demarty & Bastien, 2011; Wehrli, 2011) in spite of its greater warming potential (more than 20 times more) when compared to CO₂.

Neglecting variability in GHG emissions over time may equally cause great errors in estimations. Especially because GHG emissions reduce as reservoirs age (Barros et al., 2011). Furthermore, fluctuations in carbon cycling may occur on a seasonal (Wang et al., 2011) and even on a daily basis (Roland et al., 2010). The changes in GHG emission rates with time makes the full assessment of the carbon budget in a reservoir is a difficult task. Future studies

of GHG emissions from reservoirs should, thus, seek for a better understanding of the patterns of variation on GHG dynamics with time. Both long-term measurements (including several years) and intensive measurements (in a more frequent basis, e.g. hours) are needed.

Overcoming the issues related to variability of GHG emission in space and time becomes even more challenging due to extreme events (e.g. upwelling). Such events which are very hard to 'catch' may account to a major portion of the GHG emissions from a reservoir (Roland et al., 2010).

Most of the GHG assessments in hydroelectric reservoirs have looked at emissions from decaying biomass after impoundment, as related to the previous emissions (see section 2 for details). Some studies have used a full life-cycle assessment, which considers the emissions during the construction phase of dams (e.g. Chamberland & Levesque, 1996; Gagnon & Van de Vate, 1997; Pacca & Horvath, 2002). However, little attention has been given to the fact that every hydropower plant has an intrinsic operation life-time after which its dam should be deactivated (Pacca, 2007). Moreover, dams may be deactivated and removed due to failures (e.g. error during construction, geological instability, poor maintenance, excess internal erosion etc.). It has been estimated that about 600 dams were removed in the last 100 years in the USA alone (Gleick et al., 2009). The removal of dams was the subject of a special issue published by Bioscience in 2002 which did not mention the effects on GHG emission.

With dam removal, part of the sediment accumulated at the reservoirs will be flushed down river if not otherwise controlled (e.g. dredged). Sediment fate is an important factor determining the amount of carbon returning to the atmosphere – a greater fraction of dredged sediment becomes available for mineralization whereas organic carbon flushing downstream rivers may ultimately accumulate the ocean (Pacca, 2007). Despite the many uncertainties regarding the effects of dam removal, it is now clear that this issue should not be disregarded by future assessments. Answering questions as "how permanent is carbon accumulation in the sediment of reservoirs?" is mandatory to a better understanding of reservoirs' role in the global carbon cycle.

With the continuous and integrated research focusing on revealing the actual role of hydroelectric reservoirs in the global carbon cycle, the gaps in knowledge tend to be reduced at a rapid pace. Recent advances have resulted in important tools for reducing GHG emissions from reservoirs through changes in reservoir management and, even more importantly, through the GHG-intelligent design and location of new hydropower plants. It is now known, for example, that future hydropower projects should seek for better GHG emission/MWh ratios by reducing flooded area to the maximum extent, removing terrestrial vegetation prior to impounding and preserving the vegetation in the drainage basin to avoid soil erosion. The research about hydroelectric projects has been promoting a new generation of scientist that are able to apply fundamental environment sciences – ecology, biology, chemistry, physics and mathematics – to issues representing global concerns. We believe that the scientific community is strongly prepared to discuss the needs for energy and environmental wellness in the future.

7. References

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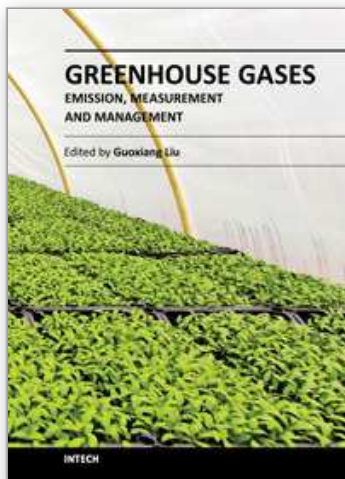
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